

Global Characteristics of Nucleus-Nucleus Collisions in an Ultrarelativistic Domain

M.V. Savina, S.V. Shmatov¹, N.V. Slavin, P.I. Zarubin
Joint Institute for Nuclear Research, Dubna, Russia

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¹e-mail: shmatov@lhe.jinr.ru

Abstract

The global observable distributions of nucleus-nucleus collisions at high energy are studied. It is shown that these distributions are sensitive to interaction dynamics and can be used to investigate the evolution of dense nuclear matter. At the LHC energy scale ($\sqrt{s_{NN}} = 5$ TeV in the heavy ion mode), a central bump over pseudorapidity plateau in the differential distributions of total transverse energy flows induced by the jet quenching effect was obtained. The energy-loss dependence on the energy for various colliding ion species was explored.

Also a new scheme for collision geometry determination is proposed as well. It is based on the correlation between transverse energy flow in the pseudorapidity interval $3 < |\eta| < 5$ and an impact parameter.

1 Introduction

Global characteristics of nucleus-nucleus collisions available in the future experiments at high energy (the LHC energy scale) are differential distributions of total transverse energy flows, $dE_T/d\eta$, as well as electromagnetic energy and charged multiplicity ones, $dE_\gamma/d\eta$ and $dN_{ch}/d\eta$. Measurements of the global distributions allows one to establish quite general rules of nucleus-nucleus collision dynamics up to the highest collision energy frontier over a widest rapidity range and verify some critical predictions of quark-gluon plasma formation models in a sufficiently simple way.

In addition to the general physics interest the global event response provides an estimate of a collision impact parameter for correlated studies in specific reaction channels like jet and W , Z^0 production.

2 Jet Quenching Manifestation in Global Energy Flows

The dense matter formation (or quark-gluon plasma) in relativistic nuclear collisions is predicted by many models [1]. One of the discussed features of such a state of a nuclear matter is energy losses of scattered partons in final state interactions with a dense nuclear matter called jet quenching [2, 3]. Among other effects originated by a jet quenching one may expect a significant modification in the differential distributions mentioned above. Indeed an indication is found for ultrarelativistic energy domain on the appearance of a wide bump in the interval $-2 < \eta < 2$ over a pseudorapidity plateau of such distributions due to jet quenching [4]. The bump existence problem rises a new question of principle – whether the asymptotic behaviour of the distributions established already at the lower energy scale will be broken in a new energy domain, or not. A calorimeter with a wide enough acceptance ($-5 < \eta < 5$) gives a chance to obtain a definite answer to the question.

Our calculations has been done in the framework of the HIJING model [5] for the energy range from 1 up to 5 TeV/nucleon. In accordance to the HIJING already $\approx 80\%$ of the total transverse energy flow are calculated by a perturbative QCD application. A minijet production (i. e. jets with $p_t \geq 2$ GeV) becomes a dominant feature of multiple processes in the considered energy region. Soft hadron-hadron processes are simulated as classical strings with kinks and valence quark ends following the FRITIOF model [6, 7].

The number of jets in inelastic nucleon-nucleon collisions is calculated in the eikonal approximation. The model provides the dependence of the parton structure function on a collision impact parameter.

The most important feature of the HIJING model is the energy losses dE/dx of partons traversing a dense nuclear matter. High energy quark and gluon losses in a hot chromodynamic matter are estimated in [8, 9]. It was shown that the dominant mechanism of energy losses is a radiative one due to a gluon emission inside a narrow jet cone (Bethe-Heitler limit) in soft final state interactions (bremsstrahlung) in accordance with the relation used in the HIJING:

$$\frac{dE}{dx} \approx \frac{C_F \alpha_s}{\pi} \mu^2 \ln \frac{3ET}{2\mu^2} \left(\ln \frac{9E}{\pi^3 T} + \frac{3\pi^2 \alpha_s}{2\mu^2} T^2 \right) \quad (1)$$

where E is the propagating parton energy, $\mu_D^{-1} \sim 1/gT$ the screening constant (Debye cutoff scale), α_s the running coupling constant. In the HIJING model this mechanism is fulfilled as consecutive transmissions of parton energy fractions from one string configuration to another.

It is supposed that energy losses are proportional to a distance l passed by a jet after a last interaction and occur only in the transverse direction within the nucleus radius. An interaction proceeds until a parton jet stays inside the considered volume and the jet energy exceeds a jet production energy limit. The space-time picture of the evolution of a parton shower is not considered in the HIJING and the dense matter formation is introduced by a phenomenological way.

In fig.1 differential transverse energy distributions $dE_T/d\eta$ are presented for minimum bias Pb-Pb collision at the CMS energy $\sqrt{s_{NN}}$ equal to 5, 3, 1, 0.5, 0.2, 0.1 TeV/nucleon. A distinctive feature of the distributions is the appearance of a central pseudorapidity bump ($-2 < \eta < 2$).

One may conclude that the bump becomes distinguishable over a plateau starting from an energy value larger than 3 TeV/nucleon. For lower energy values this effect is not so profound due to smaller value of parton energy losses in the nuclei. This fact induced by decreasing the Debye screening constant of nuclear matter at a lower energy.

We followed a jet quenching sensitivity to a mass number for lighter colliding nuclei. Energy losses of hard parton jets depend on a parton path in a dense matter like $\Delta E = l dE/dx$. Therefore reduction of the colliding nucleus radii might lead to a bump reduction. This provides an additional

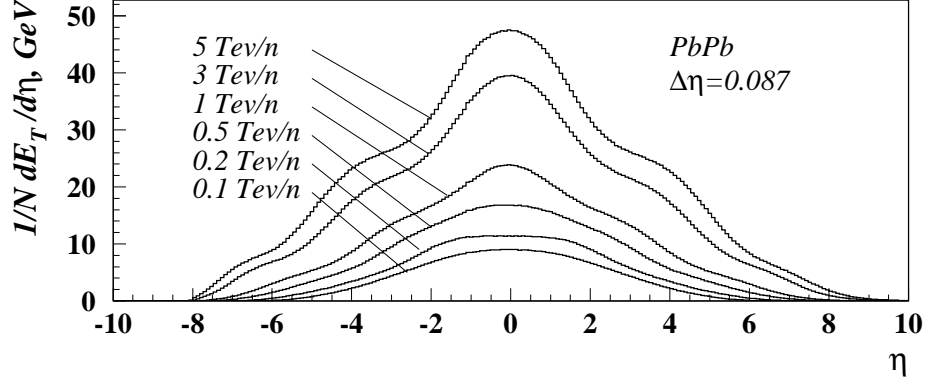


Figure 1: Differential distribution of total transverse energy $dE_T/d\eta$ (GeV) over pseudorapidity η for 10000 minimum bias PbPb collisions at $\sqrt{s_{NN}} = 5, 3, 1, 0.5, 0.2, 0.1$ TeV/nucleon. Normalized per number of events.

verification of the jet quenching effect [10]. Fig.2 shows that lead-lead collisions demonstrate maximum quenching dependence while in lighter ion cases the bump becomes less and less profound. It's interesting to note that the shadowing induced modification of the parton distribution functions can be estimated by means of absolute value measurements of the transverse energy flow density for various ion species.

3 Impact Parameter Estimation

A secondary interaction effect as a jet quenching modifies only the central rapidity part leaving both fragmentation regions ($3 \leq |\eta| \leq 5$) practically unchanged. This circumstance can be used for estimation of a collision impact parameter. The average number of minijets produced in nucleus-nucleus collisions in the pseudorapidity interval $\Delta\eta$ is related with a collision impact parameter b :

$$\bar{N}_{AA}(b, \sqrt{s}, p_0)_{\Delta\eta} = T_{AA}(b) \sigma_{jet}(\sqrt{s}, p_0)_{\Delta\eta} \quad (2)$$

where $T_{AA}(b)$ is the nuclear density overlap function of two colliding nuclei calculated with the assumption of the Wood-Saxon nuclear density distribution $\rho(r)$, σ_{jet} the minijet production cross-section.

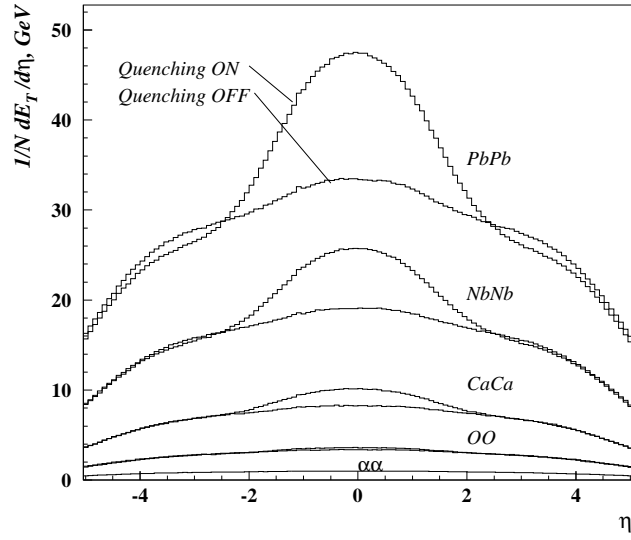


Figure 2: Differential distribution of total transverse energy flow $dE_T/d\eta$ (GeV) over pseudorapidity η for 10000 minimum bias Pb-Pb, Nb-Nb, Ca-Ca, O-O, $\alpha - \alpha$ collisions at $\sqrt{s_{NN}}=5$ TeV/nucleon with and without jet quenching. Normalized per number of events; η bin size is 0.087.

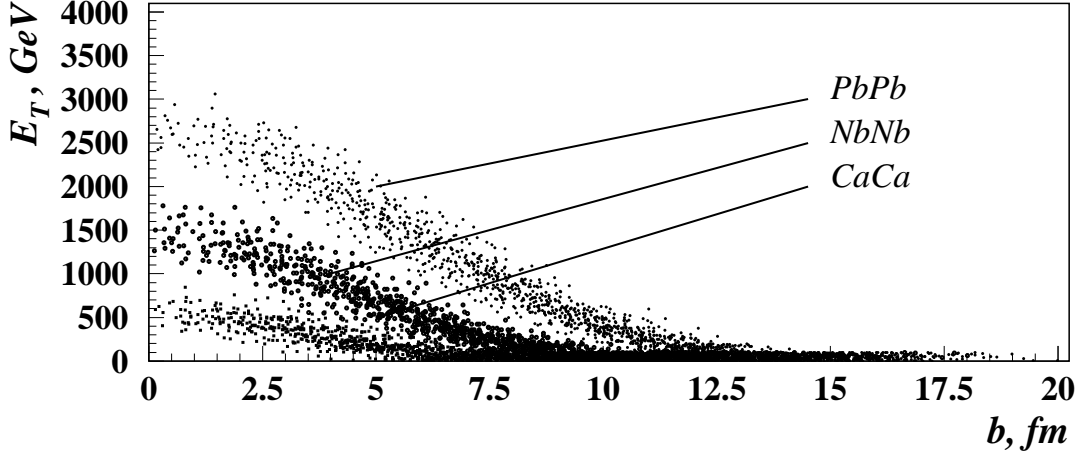


Figure 3: Correlation between transverse energy flow per collision E_T (GeV) in the pseudorapidity direction ($3 \leq |\eta| \leq 5$) and collision impact parameter b (fm). From top to bottom: PbPb, NbNb, CaCa collisions at $\sqrt{s_{NN}}=5$ TeV/nucleon.

An average transverse energy flow in $3 \leq |\eta| \leq 5$ intervals is related with a collision impact parameter as

$$\bar{E}_T(b, \sqrt{s}, p_0, 3 \leq |\eta| \leq 5) = T_{AA}(b) \sigma_{jet}(\sqrt{s}, p_0, 3 \leq |\eta| \leq 5) < E_t >_{\Delta\eta} \quad (3)$$

where E_t is the mean transverse energy per a minijet. The experimental data shows that parton structure functions used to calculate $\sigma_{jet}(\sqrt{s}, p_0, 3 \leq |\eta| \leq 5) < E_t >_{\Delta\eta}$ stay relevant until transverse energy per minijet $E_t \leq 300$ GeV. In the considered pseudorapidity range the minijet energy E_t is of the order of 10 GeV. Thus, in this way the nuclear collision geometry (i.e. impact parameter) can well be defined by means of the wide acceptance calorimeter with minimal dependence on collision dynamics details in the central region.

Fig.3 shows correlations between E_T and b for CaCa, NbNb, PbPb collisions allowing to conclude that an impact parameter can be estimated with 1.5 fm precision.

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